Value Generation in Front End Design with QFD and Multi-Attribute Utility Theory: A Social Housing Case Study

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Abstract

The design of social housing is a multi-faceted endeavour like in many social projects such as megaprojects whose expected benefits reach beyond a handful of stakeholders. Understanding the requirements of such projects can be a painstaking endeavour and without a structured process to guide decision making, such projects often fail to deliver on their intended benefits. This paper examines how the use of Utility Theory and Quality function deployment (QFD) can serve as a useful basis to support the delivery of such benefits. The research examines a social housing project in Brazil to draw focus on contextual influences on understanding, structuring and delivery of benefits. The approach adopts QFD for requirements management while Utility Theory (UT) assesses utility decision making in raking the housing models on the basis established user requirements and derived design requirements (DRs). While a medium low-income model is preferred best, the next preferred models are very-low, medium-low, medium-high in the order. The analysis indicates no transitivity in preference from an end-user perspective. The novelty of the paper is representing, quantitatively, a process of requirements management that supports the delivery of project benefits on a Utilitarian basis in social housing design. The method is able to account for interdependencies between design and user attributes in supporting social housing design decision making in an integrated process. This understanding can be key to the delivery of the right social projects that reflect context-specific end-

user needs.

Keywords: Value Delivery, Front End Design, Multi-Attribute Decision Analysis, Utility Theory, Quality Function Deployment

1. Introduction

There is a growing recognition that far too many Architecture Engineering and Construction (AEC) projects are failing to deliver on their intended project benefits (Tezel et al., 2018, Eagan, 1998). This is despite the increasing body of knowledge around the need for value performance of projects in AEC sector (Smyth et al., 2018, Tezel et al., 2018, Fuentes and Smyth, 2016). Some authors have attributed this endemic challenge to complexity inherent in construction processes (Luo et al., 2017, Bakhshi et al., 2016, Chapman, 2016, Floricel et al., 2016, He et al., 2015, Lu et al., 2015, Giezen, 2012); while others such as Locatelli et al. (2014) and later Locatelli et al. (2017) have sought a link to contextual factors. Moreover, many authors such as Smyth et al. (2018), have sought to evolve the understanding of project objectives to the wider value underperformance of such projects beyond the traditional constraints of time, cost and quality that's dominated much of recent research and practice. In view of value delivery of projects there's also the emergent concept of benefits realization in which projects are viewed in a new light of their intended and derived benefits to end user (Bradley, 2016, Serra and Kunc, 2015, Kagioglou and Tzortzopoulos, 2010, Esteves, 2009, Sapountzis et al., 2008). The existing benefits realization approach according to authors such as Serra and Kunc (2015) is that of strategic value driven from an organizational-portfolio-program-project interface; while other research has attempted to link it back to the task-activity-process-project advocated (Bølviken and Koskela, 2016, Bertelsen and Koskela, 2002, Koskela, 2000, Koskela, 1992). The nature of, social housing and social projects, in general, appears better represented by the latter approaches i.e. a focus on value delivery from a project processes perspective. This position supports design activities particularly in Front End Design (FED) that's in the main a knowledge intensive, dynamic and prone to context specific influencing factors (Arroyo et al., 2018, Arroyo et al., 2014). An emergent body of literature draws focus on the role of value generation in AEC design stages more generally (Almqvist, 2017, De los Rios and Charnley, 2017, Kpamma et al., 2017, Cardoso et al., 2016, Abrishami et al., 2015, Arroyo et al., 2014, Ballard and Koskela, 2013). Ballard and Koskela (2013) discuss the philosophical and historical roots of design and its essential role in AEC processes; Kpamma et al. (2017) highlights the role of integrated design processes; Arroyo et al. (2018) and earlier Arroyo et al. (2014) see design as a decision making process with trade-offs among often conflicting criteria. Abrishami et al. (2015) discuss insufficiencies in current processes to support design discourse; while Cardoso et al. (2016) describe the design as a problem-solving process and De los Rios and Charnley (2017) discuss design's value role as a social construct. However, despite this substantial body of research, there appears to be no research to date to draw out specificity in FED processes in relation to socially oriented AEC projects. Literature is also limited on the specific FED decision making and its contributing role to benefits realization in AEC. Thomson et al. (2006) have argued therefore that value generation in the process still remains a wider challenge in the AEC.

2. Literature Review

Failure of benefits realization in AEC has been considered on many research fronts such as Yates (1993) examination of delays in the construction process; cost overruns studies by Becker et al. (2014) and Love et al. (2013); while authors such as Swarup et al. (2011) and Battikha (2002) among others have discussed general project quality underperformance.

While these are reflective of the general waste among processes, Won et al. (2016) highlight the wider inherent and cross process nature of waste in AEC. They argue that a lot of construction waste in downstream processes can be traced back to design stages. The authors add that this leads to non-value adding processes including reworks, over processing, inventory (work in progress) and over-designs/overproduction, among others. More particularly, recently Oh Eun et al. (2016) argued that problems of constructability were a result of insufficiency in FED processes. As a result, various research and authors such as Lindhard et al. (2019) have discussed measures to address this and numerous other waste through such actions as reducing variability. The incomplete and unstructured information flow and insufficiency in requirements management processes have also contributed to the 8th Waste – *'making-do'* (Koskela, 2004). Waste in this understanding appears to result and to be a result of, poor and unstructured decision making. Smyth et al. (2018) reinforce that project success can be regarded as outcomes from a successful decision-making process. Despite this link between decision making and value generation, the exact dynamics of the two intertwined key conceptualisations in FED is limited, particularly in AEC projects of wider social benefits. Ross et al. (2004) introduce the MADA as a way of capturing, representing and managing of the dynamics in FED processes. They argue this introduces systematism to the processes to address the inherent limitations in addressing ambiguity in current design practice. They add that by capturing the decision maker's preference structures to support decisions and processes, there's improved communication. Moreover according to Malak Jr et al. (2009), the lack of structure can precipitate a state of indeterminacy. Structured decision making therefore can be seen to be a key element in success of design processes.

Cardoso et al. (2016) position on design as a problem-solving endeavour is vital in drawing focus on the need for design processes to capture User Requirements (URs). Hsu et al. (2011)

and later Hsu et al. (2012) argue that users are knowledge and ultimately value co-creators in the process. Smyth et al. (2018) have argued that value co-creation is key to benefits realisation and value delivery. It's a critical element of understanding URs according to Thyssen et al. (2010) though they immediately acknowledge its complexity. Thyssen et al. (2010) argue that because of the varied set of stakeholders often involved, URs will often be diverse and conflicting. Ultimately, decisions in FED are just as broad and varied when additional contextual influences are considered. FED is thus a process of management and transformation URs into DRs through decision trade-offs across the consequence space. Smyth et al. (2018) therefore describe this process of value co-creation and delivery as an endeavour in benefits realisation marking a successful evaluative decision making.

Moreover, Lawson (2005) argues it as a delicate balance between personal and professional biases on the one hand; and the design context on the other. The rest of this paper discusses a dynamic decision support framework for a mix of social housing models in Brazil. It's based on Quality Function Deployment (QFD) and Multi-Attribute Utility Theory (MAUT). With a social housing perspective, this paper has identified the URs from interviews and literature as low energy and maintenance, Security and Comfort in the home, durable materials, Ample Space, Ventilation, Safety within the home. The choice, weighting and normalisation of the above criteria is based on multi-objective optimisation ratio analysis (MOORA). MOORA is a strong basis for drawing out the varying intensities of interactions between and among the URs and DRs. Contextual issues about social housing considered from a design perspective in this paper include Constructability, Compliance, Functional Space, Materials Use, Design Form, Costs, Service Areas and the nature of the site.

2.1. Front End Design

FED sometimes known as Front end Planning has been identified as the most important process of a building's lifecycle (Hwang and Ho Jia, 2012, Gibson et al., 2006). It's the stage in a project's life cycle when key project processes including ideation, business case definition, project case, purpose, scope and goals definition, benefits; risk and value management, funding, stakeholders plan, outline designs and execution plan are defined (Scherer et al., 2016, Sinclair, 2013, Lawson, 2005). FED can, therefore, be described as the whole product development process that precedes the concept design (Samset and Volden, 2016). FED is the interface in the project life cycle that supports testing of ideas and alternatives, innovating and dialoguing between and among stakeholders and end-users. There is now an emerging position of the need to understand the role of FED in value generation and benefits delivery among AEC. It's been described as the first line in the link between FED processes and participatory design. Laurent and Leicht (2019) are among a growing number of authors who have widely discussed the critical importance of collaboration to project success. It's the stage in which early collaborative opportunities can be explored and established, especially around URs capture and their transformation into DRs (Kpamma et al., 2017). Kpamma et al. (2017) are among several authors that note the limited conceptual knowledge of this stage among the wider AEC sector. The problem has been attributed by some authors to the entrenched fragmented traditional approach to AEC processes (Tezel et al., 2018, Fuentes and Smyth, 2016). Other authors have argued that FED is still largely ignored as well as underestimated as an anchor to value generation in the project life cycle (Austin et al., 2001).

Moreover, Choo et al. (2004) note that FED is characterised by intensive information exchanges among stakeholders in a highly dynamic and iterative process; with the highest intensity of collaborative value creation (Fuentes and Smyth, 2016). Moreover, Lehtinen et al. (2019) point out that collaborative value co-creation hasn't been widely considered in practice and research. At the same time, endemic waste is highlighted in current AEC processes (Tezel et al., 2018, Eagan, 1998).

Research also points out that it’s the main factor behind the notable underperformance in projects in delivering their objectives be it in delayed, overpriced or poor quality project delivery (Elzomor et al., 2018). Authors argue that an ill-defined FED is simply a recipe for chaotic processes downstream (Fuentes and Smyth, 2016, Austin et al., 2001). It’s noteworthy to point out that value delivery extends beyond these traditional constraints of scope/time/cost, as argued by Smyth et al. (2018).

FED as a distinct and vital stage AEC project life cycle anchors value generation in all proceeding processes (Almqvist, 2017, Samset and Volden, 2016). However, Almqvist (2017) notes gaps between expected and achieved value in part due to the dynamic nature of the FED process. Authors say this is, in part, influenced by the project context (Lawson, 2005). Moreover, literature continues to support the position that context-specific complexity and uncertainty does impact on project performance particularly in FED processes (Luo et al., 2017, Bakhshi et al., 2016, Locatelli et al., 2014, Pich et al., 2002, Williams, 1999). Understanding FED and the contextual influences on decision making is, therefore, an essential element in underscoring value generation and benefits realisation of projects.

In determining the mission project need, the project harnesses the wide variety of information to, for example, justify why a housing project will be needed. The need case such as business objective is a basis for scoping out of the project. In FED, the high project purpose and any high-level goals have to be defined. This respects Turner and Cochrane (1993) argument that in reality, many of the low-level project goals and execution methods are merely emergent something that inherently contributes to project complexity. In dynamics contexts, FED is faced with even more complexity and uncertainty. Baccarini (1996) has argued that there's still limited knowledge about the true nature of project complexity in defining project goals and methods.

Moreover, according to Williams (1999), much of the downstream project complexity results from these poorly defined goals and methods. Cost-benefit trade-offs on the hand are essential in informing any funding mechanisms taking into account any project risks. The risk management processes identify, defines, manages or mitigates risks (Adeleke et al., 2017). The role of FED in facilitating planning, modelling, controlling and evaluation of the project processes is thus critical to success according to San Cristóbal (2017). This means harnessing stakeholder engagement as widely as possible, so that decision making is based on widely integrated information as to the purpose, goals and benefits the project has to realise. Outline designs and execution plans are thus an essential part of FED on this basis as they facilitate the development of alternatives. These processes can be facilitated by QFD in capturing and contextualising of user and DRs in FED. However as observed by Liu (2011), QFD is limited in accounting for uncertainty in the form of ambiguity and imprecision (Malak Jr et al., 2009); in decision making something that utility theory and multi-attribute decision analysis tools can and have been applied (Pergher and de Almeida, 2018). This extends QFD capabilities.

2.2. Quality Function Deployment

Quality Function Deployment (QFD) has been extensively used in many manufacturing and business processes to capture, model and refine URs commonly referred to as the voice of the customer (VOC) into designs (Babbar and Amin, 2018, Akbaş and Bilgen, 2017, Yazdani et al., 2017, Mallon and Mulligan, 1993); that enhance value for the end-user (see Table 1). Its benefits have yet to be considered for AEC especially for FED for which it's robust requirements transformation approach has brought many benefits for the manufacturing sector beyond the occasional applications such as Eldin and Hikle (2003) pilot study. One of the key processes in FED is requirements management including capture, definition and transformation into DRs through a trade-offs process. This process is, however, still insufficiently understood and applied specifically at the FED, which results in a disconnect between designers and end-users. QFD is one of the tools that's been used widely in requirements management to bridge this gap (Hoyle and Chen, 2009, Karsak, 2004).

Karsak (2004) describes QFD as a customer focused and integrated approach aimed at increasing satisfaction in new or improved products that includes elements of marketing, design, manufacturing, among others. According to Ignatius et al. (2016) and Yazdani et al. (2017), QFD is an essential step in establishing the relationships between and among URs and DRs on the one hand and the selection criteria on the other. Using the *'House of Quality'* (HOQ) approach, QFD uses a quantification mechanism to define the 'WHATs' and 'HOWs' of a value proposition through harnessing the VOC (Kassela et al., 2017, Zhang and Chu, 2009). The benefits of QFD are documented at between process and organisational levels (Kassela et al., 2017, Zare Mehrjerdi, 2011). Vinodh and Chintha (2011) cite opportunities in value generation by a QFD approach through reduced reworks.

However, the least stated of QFD benefits is in how it supports decision making in benefits realisation of projects mainly in AEC design processes. QFD has a strong basis for requirements management. This process requires decision making through trade-offs by considering the consequences of the URs against the project constraints. This is a central element of FED processes.

An adapted design house of quality applied in this paper is presented in Figure 1 with nine rooms. Room 1 represents the **first stage** in the process of applying the DQFD in decision support. It is the user requirements capture stage which is immediately followed by weighting their relative importance. In **room 2**, is a correlation matrix of the user and DRs.

Figure 1 Framework for Utilitarian Design QFD (DQFD)

Stage 3 is identifying the DRs and development of pairwise comparisons. This allows for capturing inner interdependences between them in **Room 3,** including establishing their target utility maximisations. **Room 4** is the relationship matrix between the URs and transformed DRs. The technical importance of the requirements is assessed in room 5 while rooms 6, 7 and 8 are where benefits are defined, utilities of the attributes are assessed, and requirements forecasted respectively. Finally, is the value assessments with knowledge of alternatives value propositions. **Stage 4** is the QFD analysis process of assigning priority weights to the DRs. A nine-point scaling is adopted as Extremely not important (1), Not Very important (2), Not important (3), less important (4) important (5) more important (6) Very Important (7) Extremely Important (8) and Most Important (9). **Stage 5** is the establishing of the impact matrix between the WHATs and the HOWs pronouncing on the degrees of that relationship of how one affects the other based on a four-point scaling of Weak (1), moderate (3), Strong (6) and very strong (9). **Stage 6** is the last of the steps in which the derived matrix is computed and normalised for weights to be applied in the initial alternative model's evaluation. In the DHOQ/DQFD approach, the assessment of attributes is captured in a quantifiable way. However, the reflection of these assessments given the alternatives is difficult to assess. Rooms 5, 6, 7, 8 and 9 are essential in extending the conceptual basis of QFD to a Utilitarian assessment that looks at the alternative utilities and value judgements.

2.3. Utility Theory

Utility Theory is a multi-attribute decision analysis (MADA) approach that focusses on the utility of decision making from a set of alternatives. (Trivedi and Singh, 2017, Lennon et al., 2013, Malak Jr et al., 2009, Elmisalami et al., 2006). Utility Theory analyses the nature of the decision maker's utility function to assess 1) the reward maximising choices and 2) consistency of their choices during decision making (Schultz et al., 2017). This is especially important in capturing the dynamics of decision making in FED where dynamic contextual influences and the protracted process involving many stakeholders means many decisions demand a formal structure and analysis.

Many MADA methods have been used widely to support decision making in AEC including energy (Akbaş and Bilgen, 2017, Trivedi and Singh, 2017, Lima-Junior and Carpinetti, 2016, Zhang and Chu, 2009), product development (Dong et al., 2003), AEC performance assessment (Georgy et al., 2005); and many other applications. A vital element of the design is that DRs that align to URs. A typical project can have many with different, often different subjective interpretations; sometimes conflicting in a design context. Pergher and de Almeida (2018) argue that this gives rise to the stochastic tendency in multi-attribute systems. Lawson (2005) moreover observes that end-users might not even express explicitly what their use need is. These requirements are also, at the same time, influenced by the social context of use. User value judgements are a social construct, according to Rooke et al. (2010). Beyond this, however, is the need for designers to rank conflicting URs based on their consequence. Ashley et al. (1983) have argued for the importance of sound and strategic decision making in the AEC process. The motivations of designers as part of the design process decision making in requirements transformation is just as important as the process of URs management. All these elements create uncertainty within the decision-making process. Utility Theory based on the six von Neumann and Morgenstern (1953) axioms aims to capture the trade-off dynamics including capturing of the risk propensity of designers in assessing any trade-offs.

Design processes capture the goals and desires of stakeholders to transform these into DRs. These effectively are high-level goals that are intrinsically difficult to quantify (Keeney and Raiffa, 1976). The goal of Utility Theory is in part to interpret these high-level goals into measurable objectives and ultimately attributes. A mega construction's goal of delivering an oil pipeline or bridge is, in fact, qualitative objectives. Utility theory provides a mechanism to translate these high-level objectives into quantifiable attributes that can be modelled using utility function. Utility Theory allows each criterion/attribute to be considered for its utility by defining a utility function (Dozzi et al., 1996). A criterion's utility function is a representation of a decision maker's preferences when presented with a series of options as trade-offs of the expected value of the utility. Expected Utility Value (EUV) is the aggregation of all expected utilities of a given criterion.

According to Dozzi et al. (1996), defining a utility function for any given criterion takes the three steps below for an attribute $\boldsymbol{X}$;

i) Determining the upper and lower scales of the criterion $(\boldsymbol{X}, \boldsymbol{X_L})$. A minimum of two is needed for a function to be derived.

ii) Determining the threshold $(\boldsymbol{X_T})$ - the neutral point between the two which is given a value zero; and the most preferred $(\boldsymbol{X})$ point that's set to 1. i.e. $\boldsymbol{U(x_r)_j = 0 \; and \; U(x_M)_j = 1}$

iii) Anchoring the points to define a cardinal utility and connecting the points to define a utility function either with a straight line as $\boldsymbol{U_j(x_j) = A_j y_j + B_j}$ or exponential function as

$$\boldsymbol{U_j(x_j) = A_j e^{B_j y_j} + C_j} \quad \textbf{(1)}$$

after which the utility constants can be determined.

Where;

$\boldsymbol{U_j(x_j)}$ = utility of the criterion $\boldsymbol{j}$ while $\boldsymbol{A_j, B_j}$ ***and*** $\boldsymbol{C_j}$ are constants.

Keeney and Raiffa (1976) have, however, demonstrated that the utility function is equally crucial in informing the nature of the decision maker; whether they're risk-averse, prone or neutral. Their work is quite essential in underscoring decision making in dynamic contexts with many uncertainties. They demonstrate that when a decision maker's risk premium $\boldsymbol{X_i - \widehat{X}_j}$

$$\boldsymbol{X_i - \widehat{X}_j} = \begin{cases} \textbf{Increases} \\ \textbf{Decreases} \\ \textbf{Constant} \end{cases} \quad \textbf{then the DM's UF is} \begin{cases} \textbf{Increasingly} \\ \textbf{Decreasingly} \\ \textbf{Constantly} \end{cases} \quad \textbf{Risk Averse} \tag{2}$$

Setting the optimum quantifiable and qualitative variables for the objectives, for example, can better be captured by understanding the intricate nature of the decision making the process. The utility function allows all this information to either be captured or interpreted and harnessed for consistency. In the FED, for example, it's as much essential to understand the underlying expectations of the stakeholders as it is to map out the correct processes that better deliver the project benefits.

2.4.Extending Utility Theory with wider MADA methodology

Other MADA adaptations of decision support methodologies with a utilitarian basis have contributed to its robustness including MOORA (Akkaya et al., 2015, Chakraborty, 2011); COPRAS (Mondal et al., 2017, Liou et al., 2016); ANP/AHP (Senturk et al., 2016, Zaim et al., 2014, Dağdeviren and Yüksel, 2010, Cheng et al., 2005, Saaty, 2005, Saaty, 2001); and DEMATEL (Ranjan et al., 2015). A MOORA analysis is vital in the simultaneous optimisation of conflicting criteria under certain constraints or uncertainty (Yazdani et al., 2017). A COPRAS analysis, on the other hand, is a utility analysis ranking criteria based on their utility (Yazdani et al., 2017, Ignatius et al., 2016). The combined methodology of the steps agrees with the fundamental Utilitarian principle that a decision maker will act in a way that maximises their expected utility from a lottery so that for two alternatives $\boldsymbol{Z}, \boldsymbol{W}$

$$\begin{gathered} \boldsymbol{Max}\ \boldsymbol{E}[\boldsymbol{U}(\boldsymbol{x})] = \boldsymbol{U}(\boldsymbol{y_1 x}, \boldsymbol{y_2 x}, \dots, \boldsymbol{y_l x}) \\ \boldsymbol{Min}\ \boldsymbol{E}[\boldsymbol{U}(\boldsymbol{x})] = \boldsymbol{U}(\boldsymbol{y'_1 x}, \boldsymbol{y'_2 x}, \dots, \boldsymbol{y_r' x}) \end{gathered} \tag{3}$$

$$\text{For } \boldsymbol{x} \in \boldsymbol{X} = [\boldsymbol{x} \geq \boldsymbol{0}]$$

Where $\boldsymbol{l}$ is objectives to be maximised, and $\boldsymbol{r}$ is those to be minimised. The approach to the MOORA and COPRAS is summarised in Appendix 1.

Step 1

The process starts by capturing the URs and their interrelationships through a direct relationship matrix $\boldsymbol{U}$ using the DEMANTEL method based on pronounced URs (Arabsheybani et al., 2018, Sahu et al., 2018, Patel and Maniya, 2015) such that :

$$\boldsymbol{U} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{y_{12}} & \cdots & \boldsymbol{y_{1j}} & \cdots \\ \boldsymbol{y_{21}} & \boldsymbol{0} & \cdots & \boldsymbol{y_{2j}} & \cdots \\ \boldsymbol{y_{31}} & \boldsymbol{y_{32}} & \cdots & \boldsymbol{y_{3j}} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{y_{n1}} & \boldsymbol{y_{n2}} & \cdots & \boldsymbol{y_{nj}} & \boldsymbol{0} \end{bmatrix} \tag{4}$$

Step 2

This is then normalised by (Yazdani et al., 2017):

$$\boldsymbol{X} = \boldsymbol{k}.\boldsymbol{a} \tag{5}$$

Given

$$\boldsymbol{k} = \frac{\boldsymbol{1}}{\max\limits_{\boldsymbol{1} \leq \boldsymbol{i} \leq \boldsymbol{n}} \left(\sum_j^n \boldsymbol{a_{ij}} \right)}, (\boldsymbol{j} = \boldsymbol{1}, \boldsymbol{2}, \dots, \boldsymbol{n}) \tag{6}$$

Step 3

The DHOQ is the basis for establishing the weighting for the different trade-offs between the

URs and the DRs. The decision-making process aims to pronounce itself on the relationship between the sets of paired attributes to establish the direct effect that each $\boldsymbol{ith}$ attribute exerts on each $\boldsymbol{jth}$ attribute, using a scoring range to underscore the varying influences (Yazdani et al., 2017). The computation of the total relation matrix $\boldsymbol{T}$ to capture all the dynamics of each element $(\boldsymbol{t_{ij}})$ and how indirectly it's $\boldsymbol{ith}$ criterion is influenced by its $\boldsymbol{jth}$; and is derived as follows according to Ranjan et al. (2015):

$$\boldsymbol{T} = \left[\boldsymbol{t_{ij}}\right]_{\boldsymbol{nxn}}, \boldsymbol{i}, \boldsymbol{j} = \boldsymbol{1}, \boldsymbol{2}, \dots\dots, \boldsymbol{n}$$

$$\boldsymbol{T} = \boldsymbol{X} + \boldsymbol{X^2} + \boldsymbol{X^3} +, \dots\dots, +\boldsymbol{X^k}$$

$$\boldsymbol{T} = \boldsymbol{X}\left(\boldsymbol{I} + \boldsymbol{X} + \boldsymbol{X^2} +, \dots, +\boldsymbol{X^{k-1}}\right)[(\boldsymbol{I} - \boldsymbol{X})(\boldsymbol{I} - \boldsymbol{X})^{-\boldsymbol{1}}$$

$$\mathrm{T} = \boldsymbol{X}\left(\boldsymbol{I} - \boldsymbol{X^k}\right)(\boldsymbol{I} - \boldsymbol{X})^{-\boldsymbol{1}}$$

$$\boldsymbol{T} = \boldsymbol{X}(\boldsymbol{I} - \boldsymbol{X})^{-\boldsymbol{1}}\boldsymbol{T}, \text{ when } \boldsymbol{k} \rightarrow \infty, \boldsymbol{X^k} = [\boldsymbol{0}]_{\boldsymbol{nxn}},$$

$$\mathrm{T} = \boldsymbol{X}(\boldsymbol{I} - \boldsymbol{X})^{-\boldsymbol{1}} \qquad (7)$$

The process then aims to rank the DRs through a series of normalisation and transformation of the $\boldsymbol{T}$ matrix. FED only forms part of a broader and protracted design and implementation lifecycle. Decision makers are in the main unable to pronounce themselves on a given state independently. This introduces the understanding of subjective utilities and probabilities that underpin subjective value judgements, particularly in dynamic contexts (Karni and Schmeidler, 2016).

Step 4

In this step, the vectors D and R representing the sum of the rows and columns respectively are derived as follows;

$$\boldsymbol{D_i} = \left[\sum_{j=1}^{n} \boldsymbol{t_{ij}}\right]_{nx1} = [\boldsymbol{t_i}]_{nx1}, (\boldsymbol{i} = \boldsymbol{1}, \boldsymbol{2}, \ldots, \boldsymbol{n}) \tag{8}$$

$$\boldsymbol{R_j} = \left[\sum_{i=1}^{n} \boldsymbol{t_{ij}}\right]_{1xn} = [\boldsymbol{t_i}]_{nx1}, (\boldsymbol{j} = \boldsymbol{1}, \boldsymbol{2}, \ldots, \boldsymbol{n}) \tag{9}$$

Step 5

Step 5 is the visual stage of the decision support approach in which the conflicting criteria are mapped graphically to provide insight into their causal relationships. It involves the development of the causal diagrams among criteria through a plot of $\boldsymbol{D_k} + \boldsymbol{R_j}$ vs $\boldsymbol{D_k} - \boldsymbol{R_j}$ so that $\boldsymbol{k} = \boldsymbol{i} = \boldsymbol{j} = \boldsymbol{1}$ to support the importance of one criterion over the other to establish the cause and effect groups among criteria separated by a relation axis. A positive value assigns the criterion to the causal group, while a negative one assigns it to the effect group.

Step 6

The last step is the ranking stage in which criteria weights are calculated through normalised $\boldsymbol{D_k} + \boldsymbol{R_j}$ values

The pairwise comparison matrix for the design criteria is of the form:

$$\boldsymbol{G} = \begin{bmatrix} \boldsymbol{1} & \boldsymbol{x_{12}} & \ldots & \boldsymbol{x_{1j}} & \ldots \\ \boldsymbol{x_{21}} & \boldsymbol{1} & \ldots & \boldsymbol{x_{2j}} & \ldots \\ \boldsymbol{x_{31}} & \boldsymbol{x_{32}} & \ldots & \boldsymbol{x_{3j}} & \ldots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{x_{n1}} & \boldsymbol{x_{n2}} & \ldots & \boldsymbol{x_{nj}} & \boldsymbol{1} \end{bmatrix} \tag{10}$$

<u>MOORA Analysis</u>

The MOORA analysis takes the form of the following equations:

Step 1 uses the Eq (11) to compute a normalised decision matrix of dimensionless numbers.

$$\boldsymbol{x_{ij}^*} = \frac{\boldsymbol{x_{ij}}}{\left[\sum_{i=1}^{m} \boldsymbol{x_{ij}^2}\right]^{\frac{1}{2}}}, (\boldsymbol{j} = \boldsymbol{1}, \boldsymbol{2}, \ldots, \boldsymbol{n}) \tag{11}$$

And $\boldsymbol{x}_{\boldsymbol{ij}}^{*}$ is a dimensionless number in the interval [0,1], the normalised performance of $\boldsymbol{ith}$ alternative on $\boldsymbol{jth}$ attribute

Step 2 is to weight the matrix using the following equation:

$$\boldsymbol{v}_{\boldsymbol{ij}} = \boldsymbol{x}_{\boldsymbol{ij}}^{*} \,\mathbf{x}\, \boldsymbol{r}_{\boldsymbol{ij}}, (\boldsymbol{i},\boldsymbol{j} = \mathbf{1},\mathbf{2},\dots,\boldsymbol{n}) \tag{12}$$

Step 3 involves computing for the benefit/dis-benefits is $\boldsymbol{S}_{\boldsymbol{j}}^{+}$ and $\boldsymbol{S}_{\boldsymbol{j}}^{-}$ values of the matrix using the Equation below:

$$\begin{aligned} \boldsymbol{S}_{\boldsymbol{j}}^{+} &= \sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{n}} \boldsymbol{v}_{\boldsymbol{ij}}, (\boldsymbol{i} \in \boldsymbol{J}^{\boldsymbol{Max}}) \\ \boldsymbol{S}_{\boldsymbol{j}}^{-} &= \sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{n}} \boldsymbol{v}_{\boldsymbol{ij}}, (\boldsymbol{i} \in \boldsymbol{J}^{\boldsymbol{Min}}) \end{aligned} \tag{13}$$

The Step 4 process determines the overall impact as the difference between the benefits and dis-benefits in the operation of Eq. (**14**) followed by computation of the utility ranking as a percentage of the best highest utility.

$$\boldsymbol{S}_{\boldsymbol{j}} = \boldsymbol{S}_{\boldsymbol{j}}^{+} - \boldsymbol{S}_{\boldsymbol{j}}^{-} \tag{14}$$

It's therefore essential that considerations for evolution of value judgements are taken in the process through forecasting or accounting for changing awareness in the decision making (Karni and Vierø, 2017). In terms of requirements forecasting, the consequences $\boldsymbol{c}_{\boldsymbol{ij}}$ci are defined at progressive times $\boldsymbol{t}$ against the benefits/value $\boldsymbol{b}_{\boldsymbol{ij}}$ in a matrix A (Yazdani et al., 2017). Subjective probabilities and state-dependent utilities are drawn and extended from fully known consequences at the time of decision making and allowing for these to anchor the states the decision maker is not fully aware using the general matric below

$$
A = \begin{bmatrix} c_1 & c_2 & \dots & c_t & \dots \\ b_{11} & b_{12} & \dots & b_{1t} & \dots \\ b_{21} & b_{22} & \dots & b_{2t} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{r1} & b_{r2} & \dots & b_{rt} & \dots \end{bmatrix} \quad (15)
$$

This step is also seen as necessary in assisting decision making in establishing relationships through pairwise comparisons among the requirements sets. Using this Utilitarian approach, the decision making weights in a trade-off between the cost $(\boldsymbol{c})$of an attribute today vs its benefit $(\boldsymbol{b})$ in the future time $(\boldsymbol{t})$ (Keeney and Raiffa, 1976). This Utilitarian approach adds robustness to the process of decision making by allowing for uncertainty and rationality of decision making in FED but in a quantifiable manner. This allows for an accurate account of utilities and benefits realisation of design decisions. The complementary approach forms a powerful decision support mechanism over traditional approaches to FED as it brings a robust structure to decision making to allow for life cycle thinking and decision makers to have a sense of accountability of their decisions.

3. The Case Study

This section presents the results from social housing case study basing on five design models, i.e. VL – very low, V – Low, ML – medium-low, M – medium, MH – medium-high, H – high and VH – very high-income models; from a Utility Theory and DQFD perspective. The utility analysis of attributes and generic evolution of value in FED first presented (see Figure 2). Two interfaces 1) the user and 2) the design requirements domains are identified important in identifying the necessary parameters required for a Utilitarian DQFD analysis. The project scope underscores the preliminaries of the analysis, including the project purpose and any high-level goals. User requirements are elicited based on their importance determined on a scaling using DHOQ. This forms the basis for the initial weighting of the weighting of the DRs during the analysis. This follows a process of trade-offs during which consequences are determined to define the states both known (for utilities) or not fully known (borne out of uncertainty in decision making). Beyond the design requirements domain, the analysis can use projections based on time costs today of future benefits in determining requirements forecasting using cost/benefit.

The alternatives for low, medium and high-end users were determined. URs and DRs for the design of low, medium and high-end social housing are shown in Table 1.

Figure 2 QFD Utility Theory Design Interface

3.1.Introducing the Framework

Dong et al. (2003) proposed an integrated QFD and Utilitarian MADA framework for a life cycle cost assessment of products. While the approach was effective in yielding a green approach to product life cycle design, there hasn't been any broad appeal beyond this seminal work. In a QFD approach, according to Buttigieg et al. (2016) the 'HOWs', the outputs of a stage that are a result of the inputs 'WHATs can, in fact, be the inputs of the proceeding stage. This is especially important for the new framework to account for FED iterative processes. The Utilitarian-QFD phase of the proposed framework is a basis for a robust URs and DRs trade-offs decision-making interface taking into account the contextual influences on design decisions. This is important in underscoring motivations behind decisions in assessing benefits and utilities of designs through analyzing the decision maker's utility function.

Figure 3 Processes in FED Utilitarian DQFD

In **level 1,** the DQFD process establishes the basis for the project idea, including evaluation of all alternative ideas on the way to defining the project purpose. This means also capturing the project context and defining any high-level goals. In **level 2**, the goals and methods are embedded in the design process. This is a process of defining lower level goals and capturing

URs. It also means defining the importance of these requirements and assessment of any trade-offs against any technical feasibility.

In **level 3** involves deriving the function specification and development of alternatives. An integrated and collaborative approach ensures a wider evidence base to support decision making at this stage. However, it’s essential that a mechanism for this information exchange is present so that information does reflect contribution to value generation.

Level 4 explores the modelling alternatives and mechanisms for information exchanges among stakeholders. Also important to consider in the DHOQ at this point is the specification of design characteristics and resource management mechanisms including for materials, people, finance and the site. By considering alternatives, this can form a basis for identifying any improvement areas based on the shared information from the various stakeholders.

Finally, in **level 5,** the DQFD process evaluates the benefits and utilities of the implemented DRs against the user the requirements captured in the initial stages. Also notable in this level is how the design can integrate future changes through requirements forecasting. This ensures the DQFD takes a life cycle approach.

4. Methodology

A mixed methods approach is used for this study. This forms part of the broader research into understanding the influence of contextual decision making during FED on value delivery of social housing in dynamic contexts (Guetterman and Fetters, 2018). A case study was undertaken through unstructured interviews with nine senior designers with two design firms in Brazil working on local housing projects. Brazil’s strong sociocultural and political influences, particularly in AEC processes, are considered necessary in relation to 1) value judgements and 2) in defining a specific context. The selective choice of the research participants is also deliberate in capturing local expertise in AEC for the expert participants and dwellers that have since moved into the housing units under study for capturing the URs data. To understand the nature and importance of the housing URs, unstructured interviews were carried out with 50 current property dwellers. Lastly, interviews with three senior academics with many years of specialism in AEC were undertaken. The use of these mixed methods is vital in understanding the dynamics of URs in room one of the proposed DHOQ approach demonstrated in Figure 1. DRs transformed from URs, on the other hand, are elicited using from the expert practitioners and experts to inform room 3 of the DHOQ. This group of respondents is also vital in drawing contextualization in the correlation matrix in room 2. Through interviews and questionnaires, judgements are sought and averaged as to the importance of the requirements and how these are influenced by each other. A scale of 1,3,6 and 9 is widely adopted for the HOQ importance weighting for the matrix (Yazdani et al., 2017). The framework in Figure 1 is extended in the methodological approach by Figure 3 underscoring the detailed nature of FED processes.

Five general spaces/phases in design process are identified, i.e. – 1) Ideation (Scherer et al., 2016), 2) Requirements Capture (Chen and Kim, 2017, Battikha, 2002), 3) Outline Planning (Sinclair, 2013, Linfeng et al., 2011), 4) Validation and Evaluation (Won et al., 2016) and 5) Requirements Forecasting (Chen and Kim, 2017). The general structure, according to the above authors is to capture the user requirements, identify the attributes and define them; and after that interface this with the tradeoffs spaces during decision making. Finally, a validation and evaluation process follows. A requirements forecasting process is important in casting the project in the perspective of its immediate and future utility and value. The extended framework also draws on the importance of evidence gathering, development of alternatives including outline designs, analysis of conflicting requirements and alternatives to support decision making. In later phases, decision-makers can use this knowledge basis and evidence to explore opportunities for requirement and utility forecasting, evaluation of attribute utilities and the value space. In **Phase 1**, the participants assign weighting to housing URs. These are checked with expert participants to gain underscore the correlation matrix taking into account the design alternatives. In **Phase 2**, the weights are normalized for the respective URs and adopted for the QFD analysis and ultimately in the weighting the DRs. In **Phase 3**, a Utility theory assessment of the utilities is carried out. The utility assessments are based on the adopted DRs and the utilities they yield over the design model rankings taking into account the appropriate levels. Utility Theory assigns a utility to each level of attributes or attribute clusters and attributes themselves so that the most desired out is assigned a value of $\mathbf{1}$ and the least $\mathbf{0}$. The levels are assessed from expert participants on seven attributes and form the basis for attribute comparison.

4.1.Implementation

Table 2 is a summary of the design and user requirements elicited from the interviews together with their corresponding annotations. The corresponding annotations, as adopted in the analysis, are also listed. Also presented in Table 2 is the derived utility assessment and identifying the maximisation or minimisation goals of the outcomes. From this table, first, a direct relationship matrix captures the interdependences among user requirement (see Appendix A). This is the basis of the normalisation following the Yan and Ma (2015) and Kwong et al. (2011) approach. Normalisation uses Eq. (5) and the results presented in Appendix B. The normalisation reveals a strong influence from comfort (0.1404), low energy (0.1316) and safety (0.1228) of the desired home while low maintenance (0.0614) ranks least in terms of user feedback.

The total influence matrix in Table 3 is then computed using Eq. (7). The table summarises the individual parameter to parameter influence score among user requirements.

The graph in the figure in Appendix C summarises the $\boldsymbol{D_k} + \boldsymbol{R_j}$ vs $\boldsymbol{D_k} - \boldsymbol{R_j}$ cause effect relationships. The segregation of parameters indicates that sense that Low Energy, Low maintenance, Security and Ample Space have an effect relationship while Costs, Durable materials, Ventilation and Safety are cause relationships. The latter group appears to have a much profound impact on the former than the other way round because of its higher intensities. These arise from the results of Table 4 capturing the influences of the various D and R vectors. Table 4 also captures the causal and effect results and well as weights for the URs represented as normalised $\boldsymbol{D_k} + \boldsymbol{R_j}$. The derived causal diagrams of both the URs and DRs are captured in Appendix D (a) and (b) respectively.

The process then proceeds to analyse the transformation URs into DRs using expert input and elicitation an essential step in the DQFD. This trade-offs process in decision making is the basis of the direct interpretation of the URs in a FED process perspective (Yan and Ma, 2015). The QFD approach of defining the ‘WHATs’ from the ‘HOW’s’ thus follows as outlined previously in section 2.2 and the resultant matrix from the URs and DRs and summarised in Table 2. These rankings are elicited using open structured interviews from expert designers and academics. This, in a Utilitarian approach, allows the analyst to ensure the subjective views of the decision maker are consistent over their utility function. The table is a representation of their interpretation of the interactions of the various URs/expected benefits in relation to design practice through the consequences (see Figure *2*). These are then weighted and normalised.

Simultaneously, pairwise comparisons of DRs based on each design model, i.e. $\boldsymbol{VL}, \boldsymbol{L}, \boldsymbol{ML}, \boldsymbol{M}, \boldsymbol{MH}, \boldsymbol{H}, \boldsymbol{VH}$, are elicited. Table 6 and Table 7 show the pairwise comparison of each design model against each DR criterion constructability (Co) and Compliance (Cp), respectively.

Similar comparison matrices are developed for corresponding DRs and summarised in the decision matrix in Table 8. These are further analysed against the design models through normalisation and weighting, respectively. To establish a consistent scaling of the criteria, Table 8 is normalised in Table 9 with the COPRAS approach.

The analysis process then proceeds to apply utility analysis based on COPRAS (Table 9 and Table 10); and Pj, Rj values established to determine the positively contributing (benefits) and negatively contributing (non-benefits) attributes in the COPRAS and MOORA approaches respectively. In the COPRAS analysis, Qj is then computed for relative significance for each design model to give a utility ranking Nj as a percentage ranking based on the highest Qj model (Low Housing Model – 0.2466) seen in Table 10. The least Qj value, in this case, is determined to be the Very High Housing Model (VH) – 0.0817; giving a percentage utility of 33% compared to the best choice utility.

The MOORA analysis is summarised in Table 11 and Table 12. Again to establish a consistent scaling of the criteria, Table 11 are normalised using Eq (6) and Eq. (11) respectively.

In applying the MOORA analysis to the same problem, the highest Sj value is again for the (L - Low Housing Model – 0.0758) followed by the Very Low Housing (VL) Model– 0.0555 seen in Table 11. The utility ranking (see Table 12) for VL model is now 95% while the least desirable model Very High (VH) Model fares slightly lower at 24% on the basis of the best utility model L. Ranking order overall for the models is thus as $\boldsymbol{L} > \boldsymbol{VL} > \boldsymbol{ML} > \boldsymbol{MH} > \boldsymbol{M} > \boldsymbol{H} > \boldsymbol{VH}$.

Appendix D Interdependency between (a) URs and (b) DRs in Social Housing Design

Appendix E is represents the graphical ranking orders for the models for both analyses. The performance of Low Model design appears to be in the model presenting the most significant opportunities in maximising the design form (including aesthetics) and delivering on compliance while at the same time minimising materials use and overall costs and performing competitively on-site use and needs. This appears to relate strongly to the general stakeholder needs of low-cost housing that's easy to maintain, maximises site use, safe and secure for end-users while looking great something that correlates with the Hentschke et al. (2018) study of the same scheme.

On the other hand, the very-high model performs worse in areas of site use compliance and constructability. It appears that beyond the need for a large site, the complexity of such design models might be an extra burden in implementing them, including requirements for higher percentages of service areas beyond the needed functional spaces. All this can mean a less rigid compliance regime. The design form, including aesthetics, however, appears to be less of a pressing issue with the VH model though, as expected, safety is a crucial issue which increases the complexity of the design.

4.2.Discussions

This study establishes an evaluation mechanism for selection of design social housing models; based on QFD and MAUT and its derivatives to support design decisions and processes hinged on multiple URs to inform multiple DRs. Policymakers continue to grapple with the evolving challenge of meeting the social housing needs of citizens in many countries. The case for improved value delivery through optimised decision making in design processes is ever taking more prominence in AEC processes. Value perceptions being social constructs means the needs of one community can dictate specific value expectations from such developments while these continue to evolve. At the same time, AEC practice is faced with the ever-changing nature of complexity and uncertainty that bears on the design processes not least through the evolving needs and expectations of the end-users and emergent complexity of other stakeholder needs. Given this, the traditional approach to FED to change to bring more structure to it to enhance benefits realisation and value delivery through efficient and effective decision making. This paper has sought to introduce the Design Quality Function Deployment (DQFD) aiming to establish criteria for the assessment of URs and DRs on the one hand and interrelationship assessments within both sets during the design process. In this study, DQFD is introduced as a robust basis for capturing the relationship between the users and designers during FED.

It is essential to highlight that in a utilitarian perspective, the utility function is multiplicative meaning that while the low-cost housing is preferred as the best option for end-users, the decision isn't monotonically increasing in the sense that the next option is actually the lowest cost (95%/82%) and medium-low housing (80%/59%). This is consistent with both the MOORAS and COPRAS approach. Additionally, while the Very High-end design models are the least appealing to end users (24%/33%), the Medium High (53%/46%) and High End (47%/43%) design models are more preferred than the medium model (51%/42%) overall respectively. This is reflective of a Brazilian context. Uncertainty is accounted for through probability density functions in the utility function mapping expected consequences to certainty equivalents. Requirements forecasting based on utilitarian certainty equivalent principles can be explored, establishing indifference points along the decision-making process between the future and current design process. Both of these aid decision making. The results of the study are unsurprising as the multidimensional utility of the $\boldsymbol{URs}$ on one, and $\boldsymbol{DRs}$ on the other means yields an uncertain expected utility. This study confirms the need for a collaborative design process from a user perspective. The robustness of the adopted approach means FED decision making is able to proceed in an open and structured manner in which decisions are backed by evidence. The method and framework proposed promises a computationally simple yet easily adaptable approach to supporting decision making in FED based on utility theory. The robust approach is also able to simultaneously accommodate any number of even conflicting quantitative and qualitative selection attributes, while at the same time supporting an objective and logical approach value generation in the process. This, it easily captures using the DQFD approach.

5. Conclusions and Direction of Future Research

An integrated DQFD-UT model is presented for FED in dynamic contexts. QFD is a strong application in the management of URs. It's also a basis for trade-offs with the DRs forming a basis for the evaluation of the strengths of both sets of requirements and criteria through pairwise comparisons. The weighting of attributes and criteria coalesces end-users and designers in generating value for the project. Consistency checks using the Saaty (2004) ANP approach ensures that user and experts feedback can be synthesised in a manner that supports prioritisation and ranking of criteria. Further consistency by exploring the nature of the decision maker's utility function serves to reinforce the analysis processes in the same light. The complementary nature of DQFD and utility theory in their conceptualisations supports weighting, relative importance analysis and assessment of correlation between various criteria.

This paper forms part of wider research into the role and contribution of decision making in FED. A MAUT-DQFD is proposed to be evaluated with a broader case study. Similarities that satisfy utility theory are drawn from such tools as decision making trial and evaluation laboratory (DEMATEL) and MOORA to support the assessment of design process in uncertain contexts. This is reflected on the various URs and DRs analysis at various design criteria including contextual issues on social housing design such as Constructability, Compliance, Functional Space, Materials Use, Design Form, Costs, Service Areas and the nature of the site. The weighting of the interrelationships is an essential step in capturing the dynamics. While the proposed method needs further evaluation beyond the limited and focused application adopted in this paper, it’s conceptualisations none the less form a strong basis for decision support in FED.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article

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Table 1 Applications of QFD and MADA methods

RESEARCH	SECTOR	PURPOSE
(YAZDANI ET AL., 2017)	Supply Chain	Selection of Green Suppliers – using an integrated approach for that takes into account various environmental performance requirements and criteria.
(DONG ET AL., 2003)	Product Development	Product Development based on environmentally green goals and requirements management
(KARSAK, 2004, KARSAK ET AL., 2003)	Manufacturing	Develop a methodology for URs management with imprecise information
(ZHANG AND CHU, 2009)	Product Development	Develop a method with two optimisation models i.e. logarithmic least squares and weighted least squares
(LIMA-JUNIOR AND CARPINETTI, 2016)	Supply Chain - Automotive	A method to aid choice and weighting for supplier selection with incomplete information
(AKBAŞ AND BILGEN, 2017)	Energy	Use of MADA for energy saving through use of sustainable energy sources at waste water treatment plants
(BABBAR AND AMIN, 2018)	Supply Chain	Use of MADA in supplier selection with a mix of qualitative and quantitative information and amid uncertainty
(SAN CRISTÓBAL JOSÉ, 2012)	Contractor Selection	Use of MADA for contractor selection process for road construction
(SEO ET AL., 2004)	Sustainable Designs	Selection of sustainable design models for residential buildings on the basis of their environmental performance.
(Karakhan et al., 2018)	Contractor selection	Use of MADA for contractor selection process basing on their safety performance and maturity

Table 2 Summery of Elicited User and Design Requirements and Utility Assessments

DESIGN REQUIREMENTS			USER REQUIREMENTS		UTILITY ASSESSMENTS		
CONSTRUCTABILITY	Co	increase	Low Energy	LE	Maintenance Costs	MC	low
COMPLIANCE	Cp	increase	Low Maintenance	LM	Construction Costs	CC	low
FUNCTIONAL SPACE	FS	increase	Security	SY	Accidents & Illnesses	AI	low
MATERIALS USE	MU	decrease	Comfort	C	Time off Work	TW	low
DESIGN FORM	DF	increase	Durable Materials	DM	Cost of Changes	CoC	low
COSTS	C	decrease	Ample Space	AS	Time in Home	TH	high
SERVICE AREAS	SA	increase	Ventilation	V	Equity	E	high
SITE	Si	decrease	Safety	S	Running Costs	RC	low

Table 3 The total Relation Matrix of The Social Housing User Requirements

	LE	LM	SY	C	DM	AS	V	S
LE	0.0028	0.0203	0.0191	0.0177	0.0282	0.0200	0.0182	0.0191
LM	0.0185	0.0014	0.0097	0.0091	0.0099	0.0100	0.0094	0.0011
SY	0.0020	0.0277	0.0010	0.0003	0.0185	0.0274	0.0005	0.0182
C	0.0287	0.0290	0.0193	0.0008	0.0199	0.0201	0.0184	0.0192
DM	0.0185	0.0102	0.0096	0.0004	0.0012	0.0185	0.0006	0.0096
AS	0.0278	0.0280	0.0101	0.0007	0.0106	0.0019	0.0096	0.0185
V	0.0284	0.0288	0.0190	0.0008	0.0196	0.0284	0.0010	0.0190
S	0.0281	0.0284	0.0188	0.0007	0.0279	0.0281	0.0010	0.0016

Table 4 Conversion of Vectors D and R Total and net effects for each User Requirement

URS	D_K	R_K	D_K+R_K	D_K-R_K	GROUP	WEIGHTS D_K+R_K
LE	0.1455	0.1548	0.3003	-0.0093	Effect	0.1630
LM	0.0691	0.1737	0.2428	-0.1046	Effect	0.1318
SY	0.0958	0.1066	0.2024	-0.0108	Effect	0.1099
C	0.1554	0.0305	0.1859	0.1249	Cause	0.1009
DM	0.0685	0.1359	0.2043	-0.0674	Cause	0.1109
AS	0.1072	0.1545	0.2617	-0.0473	Effect	0.1421
V	0.1451	0.0587	0.2038	0.0864	Cause	0.1106
S	0.1346	0.1063	0.2410	0.0283	Cause	0.1308

Table 5 QFD Model for Design of Social Housing

HOWS (URS)	**WHATS (CRITERIA)**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
	Co	**Cp**	**FS**	**MU**	**DF**	**C**	**SA**	**Si**	**Weight**
LE				6		6	1	6	**0.163**
LM		1		1	3	6	1	1	**0.132**
SY		1	1	3	3	6		3	**0.110**
C				3	6	6	6	6	**0.101**
DM	3			6		6			**0.111**
AS	1		6		6	6	6	6	**0.142**
V	3	3	1	3	6	6	1	6	**0.116**
S		6		3	3	1		1	**0.131**
	0.807	1.358	1.073	3.132	3.239	5.346	1.863	3.692	
NORMALISED	0.039	0.066	0.052	0.153	0.158	0.261	0.091	0.180	

Table 6 Pairwise comparison of Social Housing Models for Constructability criterion

	VL	L	ML	M	MH	H	VH	
VL	1	2	3	5	7	7	9	
L	0.5000	1	2	3	6	6	9	0.3161
ML	0.3333	0.5000	1	1	4	5	7	0.2557
M	0.2000	0.3333	1	1	1	30	6	0.1751
MH	0.1429	0.1667	0.2500	1	1	2	4	0.1165
H	0.1429	0.1667	0.2000	0.3333	0.500	1	1	0.0796
VH	0.1111	0.1111	0.1429	0.1667	0.250	1	1	0.0311

Table 7 Pairwise comparison of Social Housing Models for Compliance criterion

	VL	L	ML	M	MH	H	VH	
VL	1	3	2	3	4	8	9	0.2070
L	0.333	1	4	5	6	7	9	0.2231
ML	0.500	0.250	1	5	6	8	9	0.2053
M	0.333	0.200	0.200	1	6	8	9	0.1707
MH	0.250	0.167	0.167	0.167	1	6	9	0.1156
H	0.125	0.143	0.125	0.125	0.167	1	8	0.0668
VH	0.111	0.111	0.111	0.111	0.111	0.125	1	0.0116

Table 8 Initial decision matrix for Social Housing Models

WEIGHTS	**0.0393**	**0.0662**	**0.0523**	**0.1527**	**0.1579**	**0.2606**	**0.0908**	**0.1800**
MODEL	**Co**	**Cp**	**FS**	**MU**	**DF**	**C**	**SA**	**S**
VL	0.3161	0.2070	0.2697	0.0266	0.0865	0.0834	0.0772	0.0581
L	0.2557	0.2231	0.2277	0.0242	0.0995	0.0512	0.0843	0.0586
ML	0.1751	0.2053	0.1856	0.0725	0.1050	0.1156	0.1266	0.0978
M	0.1165	0.1707	0.1270	0.1091	0.1222	0.1991	0.1202	0.1702
MH	0.0796	0.1156	0.0815	0.1676	0.2207	0.2019	0.1852	0.1874
H	0.0311	0.0668	0.0876	0.2431	0.2187	0.1862	0.1991	0.1881
VH	0.0259	0.0116	0.0209	0.3569	0.1474	0.1627	0.2075	0.2398

Table 9 Weighted normalized decision matrix for Social Housing Models

Models	Co	Cp	FS	MU	DF	C	SA	S
VL	0.0124	0.0137	0.0141	0.0041	0.0137	0.0217	0.0070	0.0105
L	0.0101	0.0148	0.0119	0.0037	0.0157	0.0133	0.0077	0.0105
ML	0.0069	0.0136	0.0097	0.0111	0.0166	0.0301	0.0115	0.0176
M	0.0046	0.0113	0.0066	0.0167	0.0193	0.0519	0.0109	0.0306
MH	0.0031	0.0077	0.0043	0.0256	0.0349	0.0526	0.0168	0.0337
H	0.0012	0.0044	0.0046	0.0371	0.0345	0.0485	0.0181	0.0339
VH	0.0010	0.0008	0.0011	0.0545	0.0233	0.0424	0.0189	0.0432

Table 10 P_J, R_J, Q_J, N_J Values For the Design Models

MODEL	P_J	R_J	Q_J	N_J	RANK
VL	0.0609	0.0362	0.2028	82%	2
L	0.0601	0.0276	0.2466	100%	1
ML	0.0583	0.0588	0.1457	59%	3
M	0.0527	0.0992	0.1046	42%	5
MH	0.0667	0.1119	0.1127	46%	4
H	0.0629	0.1195	0.1059	43%	6
VH	0.0450	0.1401	0.0817	33%	7

Table 11 Normalized MOORA Analysis

Weights	**0.0393**	**0.0662**	**0.0523**	**0.1527**	**0.1579**	**0.2606**	**0.0908**	**0.1800**
Models	**Co**	**Cp**	**FS**	**MU**	**DF**	**C**	**SA**	**S**
VL	0.6778	0.4854	0.6189	0.0551	0.2151	0.2055	0.1926	0.1396
L	0.5482	0.5232	0.5224	0.0502	0.2474	0.1261	0.2104	0.1407
ML	0.3755	0.4814	0.4259	0.1502	0.2612	0.2850	0.3160	0.2350
M	0.2499	0.4002	0.2915	0.2261	0.3039	0.4908	0.2999	0.4089
MH	0.1706	0.2710	0.1870	0.3472	0.5490	0.4979	0.4623	0.4500
H	0.0666	0.1567	0.2010	0.5036	0.5441	0.4592	0.4968	0.4518
VH	0.0555	0.0272	0.0480	0.7393	0.3667	0.4013	0.5179	0.5760

Table 12 Weighted and normalized Design Models and DRs Matrix and ranking using MOORA.

MODELS	CO	CP	FS	MU	DF	C	SA	S	S_j^+	S_j^-	S_j	RANK
VL	0.0267	0.0321	0.0324	0.0084	0.0340	0.0536	0.0175	0.0251	0.1427	0.0871	0.0555	95%
L	0.0216	0.0346	0.0273	0.0077	0.0391	0.0329	0.0191	0.0253	0.1417	0.0659	0.0758	100%
ML	0.0148	0.0319	0.0223	0.0229	0.0412	0.0743	0.0287	0.0423	0.1389	0.1395	-0.0006	80%
M	0.0098	0.0265	0.0152	0.0345	0.0480	0.1279	0.0272	0.0736	0.1268	0.2361	-0.1092	51%
MH	0.0067	0.0180	0.0098	0.0530	0.0867	0.1298	0.0420	0.0810	0.1631	0.2638	-0.1006	53%
H	0.0026	0.0104	0.0105	0.0769	0.0859	0.1197	0.0451	0.0813	0.1546	0.2779	-0.1233	47%
VH	0.0022	0.0018	0.0025	0.1129	0.0579	0.1046	0.0471	0.1037	0.1115	0.3212	-0.2097	24%

Appendix 1

Appendix A: The initial direct-relation matrix (A) for URs

	LE	LM	S	C	DM	AS	V	S
LE	0	2	2	2	3	2	2	2
LM	2	0	1	1	1	1	1	1
SY	4	3	0	3	2	3	2	2
C	3	3	2	0	2	2	2	2
DM	2	1	1	1	0	2	2	1
AS	3	2	1	2	1	0	1	1
V	3	3	2	2	2	3	0	2
S	3	3	2	2	3	3	2	0
	20	17	11	13	14	16	12	11

Appendix B The Normalized relation matrix (A) for URs

URS	LE	LM	S	C	DM	AS	V	S	
LE	0.0000	0.0175	0.0175	0.0175	0.0263	0.0175	0.0175	0.0175	**0.1316**
LM	0.0175	0.0000	0.0088	0.0088	0.0088	0.0088	0.0088	0.0000	**0.0614**
SY	0.0000	0.0263	0.0000	0.0000	0.0175	0.0263	0.0000	0.0175	**0.0877**
C	0.0263	0.0263	0.0175	0.0000	0.0175	0.0175	0.0175	0.0175	**0.1404**
DM	0.0175	0.0088	0.0088	0.0000	0.0000	0.0175	0.0000	0.0088	**0.0614**
AS	0.0263	0.0263	0.0088	0.0000	0.0088	0.0000	0.0088	0.0175	**0.0965**
V	0.0263	0.0263	0.0175	0.0000	0.0175	0.0263	0.0000	0.0175	**0.1316**
S	0.0263	0.0263	0.0175	0.0000	0.0263	0.0263	0.0000	0.0000	**0.1228**

Appendix C DEMATEL causal diagram of Social Housing URs

Appendix D Interdependency between (a) URs and (b) DRs in Social Housing Design

Appendix E Comparative Ranking of Social Housing Design Models